

# TYPE I SUPERSTRINGS WITHOUT D-BRANES

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## Abstract

Notwithstanding the central role of D-branes in many recently proposed string dualities, several interesting type I vacua have been found without resorting directly to D-brane technology. In this talk, we analyze a three-generation  $SO(8) \times U(12)$  chiral type I model with  $N = 1$  supersymmetry in  $D = 4$ . It descends from the type IIB compactification on the  $Z$  orbifold and requires only Neumann boundary conditions, *i.e.* only the ubiquitous D9-branes (pan-branes). We also discuss a large class of 6D type I vacua that display rich patterns of Chan-Paton symmetry breaking/enhancement and various numbers of tensor multiplets. Finally, we briefly address issues raised by the conjectured heterotic - type I duality and by the relation between type I vacua and compactifications of the putative F-theory.

## 1 Superstring Dualities: a Motivation

Thanks to their soft “Regge behaviour” at high energies, strings have been regarded for some time as the only viable fundamental constituents of matter [1]. More recently, extended objects (p-branes) that had made their appearance as string solitons [2] have suggested a more democratic attitude. The most fashionable possibility is a theory of membranes (2-branes) and penta-branes (5-branes), known as M-theory, that almost by definition has 11D supergravity as its low-energy limit [3]. This theory has no analogue of the dilaton, whose (undetermined) vacuum expectation value plays the role of the string coupling constant, and does not allow a perturbative expansion prior to compactification. Upon dimensional reduction to  $D = 10$  M-theory gives the type IIA superstring [4]. Upon compactification on a segment it is conjectured to give the  $E(8) \times E(8)$  heterotic string [5]. A host of conjectured string dualities find a natural explanation in terms of M-theory and of the putative 12D F-theory [6]. The latter is related to the type IIB superstring after

compactification on a two-torus. In the intricate web of conjectured dualities a central role is played by the type II solitons carrying Ramond-Ramond (R-R) charges. These have been formerly identified with charged black p-brane solutions of the string equations of motion to lowest order in the inverse tension,  $\alpha'$ . A microscopic description [7] in terms of open strings with Dirichlet boundary conditions (= D-branes) has opened the way to remarkable progress not only in the string duality realm but also in the context of black-hole thermodynamics [8]. Despite the enormous success of D-brane technology, this talk will mainly present recent results obtained in the theory formerly known as type I superstring. In order to keep it self-contained, we will start by recalling some well-known facts about strings, p-branes and dualities.

At the perturbative level, there are two rather distinct classes of superstring theories: those with only closed oriented strings (type II A and B,  $E(8) \times E(8)$  and  $SO(32)$  heterotic) and those with open and closed unoriented strings (type I). In the past, open-string models have been studied to a lesser extent than models of oriented closed strings. Though the initial proposal [10] of identifying open-string theories as *world-sheet orbifolds* of left-right symmetric theories of oriented closed strings had already been brought to a fully consistent systematization [11], phenomenological considerations have favoured 4D perturbative vacua of the  $E(8) \times E(8)$  heterotic string preserving  $N = 1$  supersymmetry. After the work of Seiberg and Witten on  $N = 2$  supersymmetric Yang-Mills theories [9], these motivations seem to become much less compelling and a rather appealing scenario is taking shape according to which different string theories should be regarded as dual manifestations of a more fundamental (MF) theory [13].

The best established of all string dualities is T-duality, a perturbative symmetry between large and small volumes [14]. After compactification on a circle of radius  $R$ , the presence of winding states in the closed-string spectrum gives rise to a striking symmetry under  $R \rightarrow \alpha'/R$ . At the fixed point of the transformation new massless states appear that enlarge the Kaluza-Klein  $U(1)$  symmetry to  $SU(2)$  through the Halpern - Frenkel - Kac (HFK) mechanism. In more complicated situations T-duality becomes an infinite dimensional discrete symmetry which acts on the internal components of the metric  $G_{ij}$  and antisymmetric tensor  $B_{ij}$ . From the low-energy point of view these are scalar fields with only derivative interactions that parametrize the space of classical vacua, known as the moduli space of the compactification. From the world-sheet point of view T-duality is a L-R asymmetric parity operation on the string coordinates,  $\partial X \rightarrow \partial X$  but  $\bar{\partial} X \rightarrow -\bar{\partial} X$ , as well as on their superpartners. T-duality interchanges type IIA and type IIB, the two heterotic theories (after the introduction of Wilson lines), as well as Neumann with Dirichlet boundary conditions for open strings. Thus, at the perturbative level T-duality is not a symmetry for type I superstrings [24]. Moreover, the asymmetric origin of the scalar fields ( $G_{ij}$  from the closed string NS-NS sector,  $B_{ij}$  from the closed string R-R sector and

the internal components of the gauge fields  $A_i^a$  from the open string sector) prevents the existence of any natural perturbative symmetry among them.

In toroidal compactifications of the heterotic string to  $D = 4$ , T-duality is conjectured to be accompanied by a non-perturbative symmetry called S-duality [15]. In the  $N = 4$  low-energy effective lagrangian, the dilaton and the axion parametrize the coset  $SL(2, R)/U(1)$ . The  $SL(2, R)$  symmetry of the lowest-order equations of motion is believed to be broken by non-perturbative (space-time instanton) effects to  $SL(2, Z)$ . The surviving symmetry, termed S-duality, includes transformations between strong and weak coupling and generalizes the electric-magnetic duality of Maxwell theory. In type II theories, transformations between NS-NS and R-R states enlarge T-duality to a symmetry known as U-duality [16]. In  $D = 4$  the discrete subgroup  $E(7, 7; Z)$  of symmetries of the  $N = 8$  low-energy supergravity includes S-duality transformations and is conjectured to survive as a non-perturbative U-duality symmetry of the full quantum theory. Turning off the gravitational interactions, non-perturbative dualities in superstring theory may help explaining the origin of some electric-magnetic dualities found in supersymmetric Yang-Mills theories [9].

## 2 p-brane Democracy and Open-String Aristocracy

Strong-weak coupling duality between charges and monopoles in  $D = 4$  admits a natural generalization to extended objects (p-branes) [2]. In  $D$  dimensions the dual of the  $(p+2)$ -form field strength of a  $(p+1)$ -form potential is a  $(D-p-2)$ -form. This is the field strength of a  $(D-p-3)$ -form potential naturally coupled to a  $(D-p-4)$ -brane. Electric-magnetic duality in  $D$  dimensions thus exchanges  $p$ -branes and  $(D-p-4)$ -branes [2]. As a corollary strings are believed to be dual to penta-branes in  $D = 10$  and to strings in  $D = 6$ . In the latter case, a candidate dual pair is provided by the heterotic string compactified on a four-torus and the type IIA superstring compactified on a K3 surface [16, 4]. At points in the moduli space  $SO(20, 4)/SO(4) \times SO(20)$  where the abelian gauge symmetry  $U(1)^{24}$  is enhanced through the HFK mechanism in the heterotic string, one expects the appearance of new massless states in the type IIA string. These states should be charged with respect to R-R vector fields and cannot belong to the perturbative spectrum.

Non-renormalization theorems in supersymmetric theories, that guarantee the stability of states saturating the Bogomolny - Prasad - Sommerfield (BPS) bound between mass and central charges, suggest an interpretation in terms of BPS solitons. In  $D = 4$ , these states are to be identified with charged extremal black-holes [16]. From the higher (ten/eleven/twelve) dimensional point of view these states may be pictured as p-branes

wrapped around internal dimensions. When a homology cycle of the internal manifold shrinks to zero size, a conifold transition may take place and the solitonic state whose mass is proportional to the size of the cycle becomes massless [17].

Recently these ideas have attracted much attention in connection with the observation that non-perturbative corrections in the string coupling  $g$  may be as large as  $\exp - \frac{1}{g}$ , rather than the expected  $\exp - \frac{1}{g^2}$  [7]. Since a boundary contributes one half a handle to the Euler characteristic of the world-sheet, the open-string coupling constant is the square-root of the closed string one. Thus, non-perturbative effects of the above kind are naturally generated by the introduction of boundaries, *i.e.* by coupling open strings to the closed string spectrum. Type II theories admit solitonic p-brane solutions which couple to R-R fields (with odd p in the type IIB case and even p in the type IIA case) and whose masses scale as  $M_{RR} \approx \frac{1}{g}$ . A microscopic description is possible in terms of open strings with some of the string coordinates satisfying Dirichlet rather than Neumann boundary conditions, whence the name “D-branes” [7]<sup>1</sup>. Under T-duality a Dp-brane is exchanged with a D(p±1)-brane, consistently with the interchange of the two type II theories. Simple supersymmetric configurations of D-branes correspond to parallel/intesecting Dp-branes and D(p+4)-branes. The multiplicity of parallel D-branes allows for a geometric interpretation of Chan-Paton (CP) factors.

Open strings and D-branes play a crucial role in many recently conjectured string dualities [13]. The  $SO(32)$  type I superstring may be considered as describing the excitations of a BPS configuration of 32 type IIB D9-branes. Similarly, the excitations of the type I D-string (D1-brane) exactly coincide with the (light-cone) degrees of freedom of the  $SO(32)$  heterotic string [19]. Combined with the possibility of a direct map between the 10D low-energy effective actions, this observation has led to conjecture a strong-weak coupling duality between the type I and heterotic  $SO(32)$  theories. This conjecture has passed several tests [20] and is expected to persist, in some non-naive form, after compactification [13]. In this respect, it is crucial to observe that the relation between type I and heterotic dilatons depends on the space-time dimension  $D$  according to [21]

$$\phi_H = \frac{6-D}{4} \phi_I - \frac{D-2}{16} \log \det G_I \quad , \quad (1)$$

where  $G_I$  is the internal metric in the type I string-frame. For instance, in  $D = 6$  [22], the heterotic dilaton, that belongs to the universal tensor multiplet, is related to the internal volume mode of the type I string, that belongs to a hypermultiplet [11, 28].

In the unifying picture emerging from string dualities, all p-branes should be considered on an equal footing, whence the proposed *p-brane democracy* [16]. Open strings, the

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<sup>1</sup>A R-R vertex operator with minimal, non-derivative, coupling to boundary and crosscap states was found in [24]. But only after the seminal work of Polchinski [7], the importance of the above coupling has been fully appreciated.

best known of all D-brane excitations, play however a privileged role - whence the proposed *open-string aristocracy* - in that many features that are non-perturbative in other descriptions are reachable at a perturbative level in type I vacua [11, 28].

### 3 Type I Systematics

The general construction of perturbative open-superstring vacuum configurations consists in a non-standard  $Z_2$ -orbifold procedure [10, 27]<sup>2</sup>. First of all, the conventional Polyakov perturbative series must be supplemented with the inclusion of world-sheets with boundaries and/or crosscaps. (Super)conformal field theories on surfaces of this kind are equivalent to (super)conformal field theories on double-covering surfaces endowed with a  $Z_2$ -orbifold projection of the spectrum under the exchange of left-movers with right-movers. Roughly speaking, this procedure halves the world-sheet symmetries as well as their target space byproducts as expected for BPS solitons. The truncation of the closed-string spectrum encoded in the torus partition function  $\mathcal{T}$  is implemented by the Klein bottle projection  $\mathcal{K}$ . These two contributions make up the “untwisted sector” of the parameter space orbifold

$$\mathcal{Z}_u = \frac{1}{2}(\mathcal{T} + \mathcal{K}) = \frac{1}{2}Tr_{closed} \left( (1 + \Omega)q^H \bar{q}^{\bar{H}} \right) \quad (2)$$

where  $\Omega$  denotes orientation reversal. The role of the “twisted sector” is played by the open string spectrum encoded in the annulus partition function  $\mathcal{A}$  and its projection, the Möbius strip  $\mathcal{M}$

$$\mathcal{Z}_t = \frac{1}{2}(\mathcal{A} + \mathcal{M}) = \frac{1}{2}Tr_{open} \left( (1 + \Omega)q^H \right) \quad (3)$$

In standard orbifolds, the twisted sectors have multiplicities associated to the fixed points. Similarly, in parameter-space orbifolds, the open-string states may acquire multiplicities associated to their ends through the introduction of Chan-Paton (CP) factors. Consistency requirements may be deduced transforming the above amplitudes to the transverse channel, where Klein bottle  $\tilde{\mathcal{K}}$ , annulus  $\tilde{\mathcal{A}}$  and Möbius strip  $\tilde{\mathcal{M}}$  are to be identified with closed-string amplitudes between boundary and/or crosscap states. Since “half” of the closed-string states have been projected out of the spectrum, it would be inconsistent if the latter were to couple to the vacuum. The cancellation between boundary and crosscap contributions to these tadpoles constrains the CP factors and the signs in the projections  $\tilde{\mathcal{K}}$  and  $\tilde{\mathcal{M}}$  [7, 11].

In order to explicitly solve these constraints, it proves very useful to exploit Cardy’s proposal and associate a boundary state  $|B_i\rangle$  as well as a CP factor  $n^i$  to each sector of

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<sup>2</sup>Many authors refer to these *parameter space orbifolds* as *orientifolds* though only a restricted class of the resulting models requires orientifold planes.

the spectrum. This amounts to expressing the annulus partition function as [11]

$$\mathcal{A} = \sum_k n^i n^j N_{ij}^k \chi_k \quad (4)$$

where  $N_{ij}^k$  are the fusion rule coefficients and the sum runs over the sectors of the spectrum encoded in the characters  $\chi_k$ . In the transverse channel,  $\tilde{\mathcal{A}}$  becomes a linear combination of characters with coefficients that are perfect squares thanks to the Verlinde's formula. Then  $\tilde{\mathcal{M}}$  is fixed for consistency as an appropriate “square root” of the product of  $\tilde{\mathcal{K}}$  bottle and  $\tilde{\mathcal{A}}$ . Following this procedure for rational models a web of perturbatively consistent (non)supersymmetric type I vacua may be constructed in any dimension [11, 12].

However, this is not the whole story. Indeed the above construction assumes a unique  $\mathcal{K}$ . Sewing constraints for conformal field theories on closed oriented Riemann surfaces can be extended to surfaces with boundaries and/or crosscaps and a crosscap constraint can be deduced [23]. In many interesting cases there are several solutions to this constraint which allow to deduce several different projections of the closed string spectrum. The procedure is then reversed, the number of allowed boundary states is reduced and may be inferred from  $\tilde{\mathcal{K}}$ . Many new type I descendants of type II B models can be constructed systematically. In general,  $\mathcal{K}$  allows for the introduction of signs in the projection of the closed-string spectrum. For instance, in toroidal compactifications it is possible to choose

$$\mathcal{K} = \sum_{m \text{ even}} q^{(\frac{m}{R})^2} + \epsilon \sum_{m \text{ odd}} q^{(\frac{m}{R})^2} \quad , \quad (5)$$

where the conventional choice is  $\epsilon = 1$ . When  $\epsilon = -1$ , there are no massless tadpoles, and thus one cannot introduce boundary states and open strings [28]. This procedure may be generalized to any (rational) model admitting  $Z_2$  automorphisms, and the introduction of the open-string sector is simply forbidden if  $\tilde{\mathcal{K}}$  does not involve massless characters. More general toroidal compactifications were discussed in [24]. There it was shown how a quantized background for the NS-NS antisymmetric tensor reduces the size of the CP group. Deformations of the metric as well as of the gauge fields are allowed and CP symmetry breaking may proceed via Wilson lines.

## 4 D=6: Tensors and CP Symmetry Enhancement

The first consistent 6D  $N = 1$  open-string models [11, 12] differ markedly from perturbative heterotic K3 compactifications. The open-string spectra often require symplectic CP groups and the closed-string spectra contain different numbers of (anti)self-dual tensors that take part in a generalized Green-Schwarz (GS) mechanism [25]. Recently, additional instances of 6D  $N = 1$  type I models have been constructed as toroidal orbifolds [26],

along the lines of [27]. A nice geometrical setting for all these 6D models is provided by the F-theory proposal of [6], where non-trivial scalar backgrounds allow for an effective 12D dynamics. The variety of 6D models with different numbers of tensor multiplets may then be related to a corresponding variety of compactifications on elliptically-fibered CY threefolds [6]. Many of these vacua are related to non-perturbative heterotic vacua with 5-branes in which the gauge symmetry is enhanced at the core of a Yang-Mills instanton [22].

Exactly solvable K3 compactifications also arise from Gepner models and from fermionic constructions. The starting point for a type I model is a “parent” type IIB theory, whose chiral spectrum is uniquely fixed by target-space  $N = (2, 0)$  supersymmetry. In the open descendants the surviving supersymmetry is  $N = (1, 0)$ , and the unoriented closed spectrum consists of the supergravity multiplet coupled to  $n_T^c$  tensor multiplets and  $n_H^c$  hypermultiplets. It should be appreciated that  $n_T^c + n_H^c = 21$  since all matter fermions arise from the 21 type IIB tensorini. The open unoriented sector contains  $n_V^o$  vector multiplets and  $n_H^o$  charged hypermultiplets. The tensor fields that flow in the transverse channel take part in a generalized GS mechanism [25]. The  $U(1)$  anomalies are not cancelled by this GSS mechanism, but involve the four-form dual of RR scalars, in a way reminiscent of the Dine - Seiberg - Witten (DSW) mechanism in  $D = 4$  [29].

Barring  $U(1)$  anomalies, the largest allowed CP group,  $U(16) \times U(16)$ , requires the introduction of discrete Wilson lines [12], related to Möbius projections that do not respect the accidental extended symmetry of the rational model. After Higgsing, this model, which has been termed the GP model<sup>3</sup>, seems to be connected to perturbative vacua of the heterotic string in  $D = 6$  [22]. A large class of perturbative type I vacua with different numbers of tensor multiplets, including zero, and a rich pattern of symmetry breaking/enhancement is available [28] that extends the already rich list of [11, 12]. Not all of these type I vacua admit a clear D-brane interpretation. It is tempting to conjecture that some of them should correspond to configurations of D7-branes partially wrapped around the homology 2-cycles of a K3 surface.

## 5 A Chiral Type I Vacuum Configuration in $D = 4$

The first chiral  $N = 1$  supersymmetric type I model [21] includes an open-string sector with only Neumann boundary conditions, *i.e.* open strings ending on the ubiquitous pan-brane. It has been found as the open descendant of the type IIB superstring compactified on the  $Z$  orbifold, the  $Z_3$  orbifold of a six-torus. The original massless closed-string

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<sup>3</sup>I suppose that GP stand for the initials of Gianfranco Pradisi, but I have not been able to trace the origin of this terminology in the literature.

spectrum, containing the  $N = 2$  supergravity multiplet, 10 untwisted and 27 twisted hypermultiplets, is truncated to  $N = 1$  supergravity coupled to 36 chiral multiplets. Tadpole cancellations require the introduction of open-string states with a CP gauge group  $SO(8) \times SU(12) \times U(1)$ . The resulting massless spectrum includes three generations of chiral multiplets in the  $(8, 12^*)$  and  $(1, 66)$  representations [21]. The  $U(1)$  factor is anomalous, and the DSW mechanism involving R-R axions gives a mass of the order of the string scale to the corresponding gauge boson [29]. It is worth noticing that a candidate dual heterotic model is a  $Z$  orbifold with non standard embedding. In the twisted heterotic spectrum massless states in the spinor of  $SO(8)$  appear which have no type I counterparts. In order to put heterotic - type I  $N = 1$  duality on a firmer basis it is rather compelling to understand the origin of these states and to extend the list of  $N = 1$  dual pairs.

Returning to the untwisted sector of the  $Z$  orbifold, the “parent” type IIB model includes 20 NS-NS fields  $(\phi, b_{\mu\nu}, b_{i\bar{j}}, g_{i\bar{j}})$ , and 20 R-R fields  $(\phi', b'_{\mu\nu}, b'_{i\bar{j}}, A_{\mu\nu i\bar{j}})$ . These parametrize the quaternionic manifold  $E_{6(+2)}/(SU(2) \times SU(6))$ , obtained by c-map [31] from the special Kähler manifold  $SU(3, 3)/(SU(3) \times SU(3) \times U(1))$  of the heterotic string. In the NS-NS sector, the type I projection retains the dilaton and a 9-dimensional real slice of the complex Kähler cone corresponding to  $Im(J_{i\bar{j}}) = Re(g_{i\bar{j}}) + Im(b_{i\bar{j}})$ . In the R-R sector, one is left with a mixture of  $\phi'$  and  $b'_{\mu\nu}$ , as well as with mixtures of the other R-R fields. Though somewhat surprising, this result is clearly encoded in the partition function and is also supported by the explicit study of tree-level amplitudes [30]. The 20 scalar fields parametrize a space  $\mathcal{S}_I$  that, on general supersymmetry grounds, is a Kähler manifold embedded in  $E_{6(+2)}/(SU(2) \times SU(6))$ . Group theory considerations together with some rather compelling duality arguments uniquely select  $\mathcal{S}_I = Sp(8, R)/(SU(4) \times U(1))$  [30], a generalized Siegel upper half plane. It should be appreciated that the type I truncation is vastly different from the heterotic one. Observe that  $\mathcal{S}_I$  is the space of symmetric  $4 \times 4$  matrices  $\Omega$  with positive  $Im\Omega$  and has a natural Kähler metric with Kähler potential  $K = -\log \det Im\Omega$ . The elements of  $Re\Omega$  are R-R scalars, while the elements of  $Im\Omega$  parametrize a real slice of the complex Kähler cone of the CY threefold. The symplectic group  $Sp(8, R)$  acts naturally on the “Teichmüller” space  $\mathcal{S}$  through projective transformations of  $\Omega$  and clearly includes  $S$  and  $T$  duality transformations. In particular, the continuous Peccei-Quinn (PQ) symmetry of the R-R fields corresponds to the subgroup of  $Sp(8, R)$  triangular matrices

$$S_{PQ} = \begin{pmatrix} 1 & B \\ 0 & 1 \end{pmatrix} \quad , \quad (6)$$

with  $B = B^T$ . It is natural to expect that (world-sheet and space-time) instanton effects induce non-trivial monodromies with respect to  $Sp(8, Z)$ , so that the moduli space is actually  $\mathcal{S}_I/Sp(8, Z)$ . A non-perturbatively generated superpotential would then be a



modular form of  $Sp(8, Z)$ .

The above results suggest that open descendants of type IIB compactifications on generic CY threefolds involve a new complexification of the classical moduli space. The new map for open descendants, termed “o-map” [30], associates a type II quaternionic manifold  $\mathcal{Q}_{n+1}$  to a new Kähler manifold  $K_I$  for  $(n+1)$  NS-NS and  $(n+1)$  R-R real scalars. The complexification of the Kähler class of classical CY threefolds is at the heart of mirror symmetry, that should also have a new realization in the type I setting. In this case the  $N=1$  classical Kähler manifold should receive quantum corrections from D-brane world-volume instantons [32].

## 6 Glimpses of the F-Theory

Non-trivial backgrounds for the scalar fields of type IIB supergravity have provided a geometrical setting [6] for some peculiar 6D string vacua previously derived as open descendants of type IIB K3 compactifications [11, 12]. The resulting models differ markedly from conventional K3 reductions, since their massless spectra contain different numbers of (anti)self-dual tensors that take part in the GSS mechanism [25]. These peculiar features find an elegant rationale in the compactification of a putative 12D F-theory [6] on elliptically fibered Calabi-Yau (CY) threefolds, a construction that generalizes previous work on supergravity vacua with scalar backgrounds by taking into account subtle global issues.

The simplicity of the type I model of [21] reflects itself in the linearly realized symmetry,  $H = SU(4) \times U(1)$ . The  $SU(4)$  factor strongly suggests a 12D interpretation [30] as the holonomy of a CY four-fold. The possible relation of the type I superstring on the  $Z$  orbifold to the F-theory reduction on a CY fourfold [30] can only give a hint to the richness of open-string constructions. The idea that a fundamental non-perturbative description could be democratic with respect to the various p-branes is rather appealing. Still perturbative computability tends to favour one-branes. The recent results seem to indicate that open one-branes, with all possible boundary conditions, are more equal than the others.

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